HIGH RESOLUTION BEAM ORBIT MEASUREMENT ELECTRONICS BASED ON COMPENSATED DIODE DETECTORS

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Abstract

A high resolution beam position monitor (BPM) electronics based on diode peak detectors has been developed at CERN. The circuit processes the BPM electrode signals independently, converting the short beam pulses into slowly varying signals which can be digitized with high resolution ADCs operating in the kHz range or even measured with a DC voltmeter. For signals with peak amplitudes larger than some hundred mV the non-linear forward voltage of the diodes is compensated by a simple network using signals from two peak detectors, one with a single and the second with two diodes in series. This contribution presents results obtained with the first prototype in the laboratory and with the CERN-SPS beam. Ongoing development and possible future applications of the technique are also discussed.

INTRODUCTION

Diode peak detectors have been used at CERN for processing BPM signals in tune measurement systems [1] and recently for observing beam motion of very small amplitude [2]. For these applications the detector DC components related to beam position are rejected and only AC beam motion signals are processed. Diode detectors allow direct conversion of the fast beam pulses from BPM electrodes to signals in the kHz range, which can be efficiently digitised with high resolution ADCs. These benefits allow a very high amplitude resolution to be achieved with simple and robust hardware.

The main difficulty in using a similar scheme for measuring beam position is the diode forward voltage. This voltage causes the detector output voltage to be smaller than the true peak of the input signal, introducing an important error. In the ideal case the beam position p_{AB} in the plane of BPM electrodes A and B can be evaluated from the electrode peak voltages V_A and V_B as

$$p_{AB} = c_{AB}\frac{V_A - V_B}{V_A + V_B} \qquad (1)$$

where c_{AB} is the BPM conversion factor, for simplicity assumed to be a constant equal to the BPM half aperture. If beam position is estimated from the output voltages of the diode peak detectors of electrodes A and B, which are smaller than V_A and V_B by the diode forward voltage V_d, then (1) can be rewritten as

$$p_{AB} = c_{AB}\frac{V_A - V_B}{V_A + V_B - 2V_d} \qquad (2)$$

Thus, V_d causes large beam position errors for small V_A and V_B. In reality V_d is not a constant, but varies with the detector input signal amplitude, its slew rate, temperature, making the beam position error a complex function.

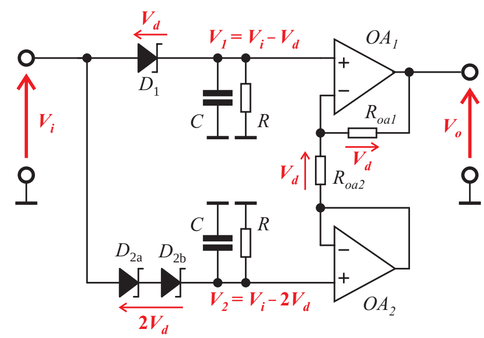

Figure 1: A compensated diode detector

The dream of the authors was to find a circuit with self-compensation of the diode forward voltage, in order to profit from the benefits of the peak detector scheme also for beam orbit measurement. The simplest and most promising scheme found is shown schematically in Fig. 1. Such a circuit diagram was published in [3], and mentioned in a popular electronics textbook [4].

The compensation scheme is based on two peak detectors, one with a single and the second with two diodes in series. The signals from two such detectors are processed with a simple network with two operational amplifiers, allowing the input peak voltage to be restored. The voltage values at circuit nodes explain the compensation scheme. The difference of the output voltages from both peak detectors is equal to the drop on one diode, V_d. As the voltage between the inverting and non-inverting inputs of the operational amplifiers is practically zero, V_d is converted into current V_d/R_{oa1} and, as the current of the non-inverting input of OA_1 is practically zero, the current V_d/R_{oa1} is converted again into V_d with $R_{oa2} = R_{oa1}$. In this way $2V_d$ is added to the output of OA_2, compensating the $2V_d$ drop on the two diodes D_{2a}, D_{2b}.

Identical voltage drops across each diode require the diode currents for both detectors to be equal, also during transients when the parallel capacitors are being charged. This is not possible with small input signal amplitudes, for which the current of the two-diode detector is smaller. Hence, the compensation mechanism does not work for small input signals. This limitation cannot be removed for pulse signals by biasing the diodes with DC current, as the symmetry of the detector pulse currents is required.

THE PROTOTYPE

The first prototype of the diode orbit measurement electronics was built as a simple circuit to test the performance of the compensated diode detectors. It was built using the PCB, power supply and mechanical parts of a diode tune measurement front-end [5]. For simplicity it has only two channels foreseen for two BPM electrodes. The prototype is built as follows:

– The compensated diode detectors (of positive polarity for proton beams) are almost as simple as the circuit of Fig. 1 and are based on small signal Schottky diodes. The three diodes of each compensated detector are in one single package for good forward voltage symmetry and thermal coupling.
– The time constant of the detectors can be increased by adding two additional parallel capacitors. Larger capacitors filter more efficiently noise of the parallel resistors [5], improving noise performance of the detectors at the expense of increasing their time constants.
– A small diode bias current can be switched on and off. This was used to study the effect of the bias current on the performance of the detectors for small input signals.
– The two prototype inputs are connected to the two compensated detectors through a simple two-by-two multiplexer built with 4 reed relays. The multiplexer is foreseen to multiplex the inputs to improve absolute measurement accuracy.
– The outputs of both compensation circuits are connected directly to the prototype outputs.
– The prototype is built from components “as they come” and there was no component selection or adjusting.
– The prototype does not have any temperature stabilisation.
– The prototype does not have any adjustable elements.

LAB MEASUREMENTS

The performance of the compensation scheme was first verified by applying a sine wave of variable amplitude on the prototype input and measuring the output voltage with a laboratory voltmeter. Both of the prototype compensated detectors were connected to one input through a relay multiplexer and this input was driven by a generator. The input matching was conserved, as the termination is done before the multiplexer and the diode detectors have high impedance inputs (in the steady state with the capacitors charged). To minimise measurement errors the output voltages of both channels were measured one after the other with the same voltmeter.

The measured conversion characteristics of a 1 MHz sine wave into DC voltage is shown in Fig. 2. A large nonlinearity is present only for input amplitudes below some 50 mVp (mV peak). The characteristics above 0.5 Vp are very linear.

The linearity error from a fit for the input signals of amplitude larger than 0.5 Vp is shown in Fig. 3. Four error curves are presented, one for each channel with the diode bias current off and on. It is seen that the measurement points for both channels are very close, indicating that the majority of the observed linearity errors come from the generator itself. The plot therefore shows the upper error bounds set by the generator. The bounds are smaller than 1 mV for input amplitudes larger than 0.5 Vp and are still smaller than 2 mV for amplitudes

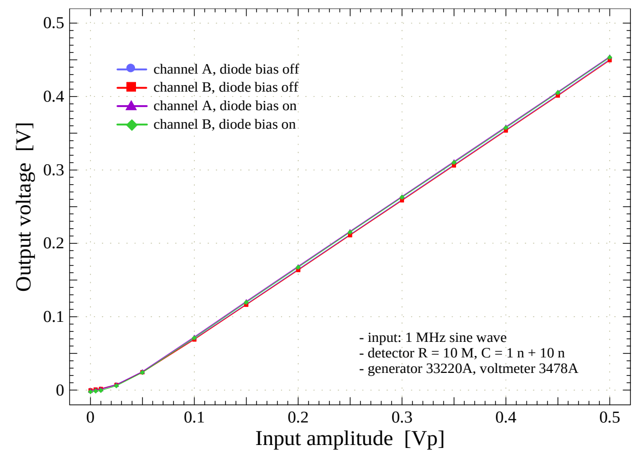

Figure 2: Prototype conversion characteristics.

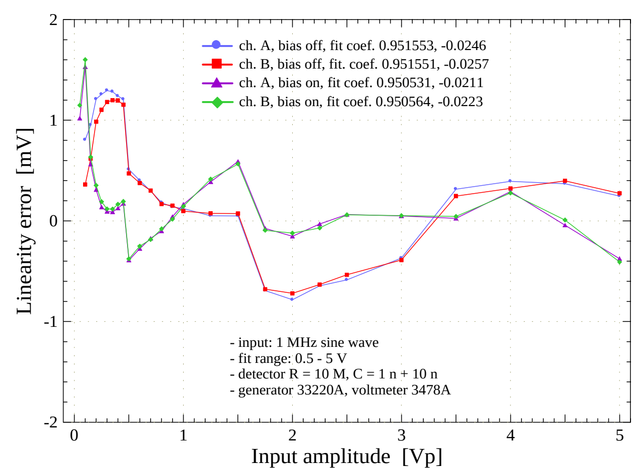

Figure 3: Linearity errors of the prototype.

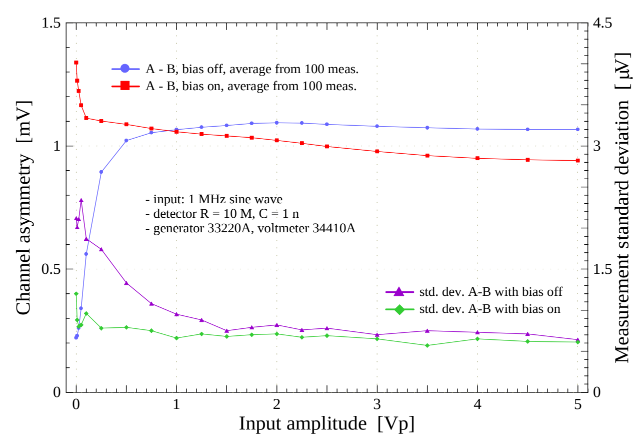

Figure 4: Asymmetry between both prototype channels.

below 0.5 Vp and larger than the voltages at which the curves start, i.e. 100 mVp and 50 mVp for bias current off and on, respectively. Note that the fit coefficients listed in Fig. 3 are remarkably close for both channels, especially the slope coefficient for the measurement with the bias current off (difference of 2 ppm). This is possible because the steady-state capacitor voltage depends little on the capacitor and resistor values. It was not the case with the

Table 1. Statistics of long-term measurement of the difference of the output voltages from both channels. Input signal: 1 MHz sine wave, 2 Vp.

observation time [h]	average [mV]	peak-peak [µV]	standard dev. [µV]
1	1.056	8	1.1
2.5	1.060	13	1.9
24	1.051	60	17
60	1.044	55	11

presence of the bias current, which in the prototype was not optimised for stability.

In order to be more independent of the limited accuracy of the input amplitude readings the following measurements were performed in a differential way, namely by measuring the difference in response of both channels to the same input stimulus. Results of such measurements taken at the 10 Hz rate are shown in Fig. 4. The measurements were carried out with a voltmeter which allowed a programmed number of acquisitions to be made and whose statistics were then calculated. The standard deviation form 100 measurements is shown, with the scale on the right hand axis. It can be seen that the channel asymmetry is close to 1 mV and changes little for amplitudes larger than 0.5 Vp. The standard deviation used to estimate the measurement resolution is extremely small in all cases, in the order of 1 µV, and go significantly lower for input amplitudes above 1 Vp. The average standard deviation for amplitudes higher than 1 Vp are 0.8 µV and 0.7 µV for the bias current off and on, respectively.

In order to determine noise of a single channel one has to take into account the fact that the above results are standard deviations of a difference of output voltages from both channels and that the voltmeter itself introduces some measurement noise. To estimate this noise the voltmeter input was shunted and the same measurements were performed, giving the standard deviation of about 0.5 µV. With these contributions taken into account, the upper bound of 1 µV of the measurements of Fig. 4 shrinks to 0.5 µV of noise on one channel.

The fact that both channels were driven from the same generator makes the measurements of Fig. 4 independent of the generator signal noise. For the output voltages from each input measured individually the standard deviations were in the order of 30 µV.

Assuming that the compensated detectors are used for the input amplitudes larger than 0.5 Vp the noise of 0.5 µV introduced by the detectors gives the measurement resolution of 1 ppm for a detector time constant of 10 ms and a measurement rate of 10 Hz. This resolution still improves by an order of magnitude if the input amplitude is increased to give 5 V at the compensated detector outputs, which can be considered as the largest value acceptable by modern high resolution ADCs.

If this 0.1 ppm resolution of the electrode peak voltage measurement could be translated into a resolution of the beam orbit measurement in the order of 1 ppm, then for a BPM with a 100 mm aperture the achievable orbit resolution would be in the order of 100 nm.

The measurement of long term stability of the symmetry of the compensated detectors is summarised in Table 1. The one hour and 60-hour peak-peak variations are in the order of 10 µV and 60 µV, respectively. This would be equivalent to an orbit measurement error in the order of 1 µm and 6 µm, respectively, for an input signal of 1 Vp and 100 mm BPM aperture.

MEASUREMENTS WITH BEAM

Typical signals from the prototype compensated diode detectors installed in the CERN-SPS are shown in Fig. 5. The beam signals came from two horizontal electrodes of a stripline BPM through some 300 m long cables. As the bandwidth of the diode detectors extends down to DC, the signals went through RF transformers in order to break ground loops and remove potential low frequency interference captured by long input cables. The detector output signals were digitised with a sampling oscilloscope operated in a high resolution mode.

A record of three SPS cycles with different total beam intensities is shown. The detector output signals are BPM electrode peak voltages, which depend not only on the beam position, but also on beam intensity and bunch length. The corresponding normalised horizontal beam position calculated according to (1) is shown in Fig. 6. It can be seen that the beam position variations along each of the cycles are quite reproducible, in spite of the fact that the overall beam intensity from the different cycles vary significantly, which is compatible with the detector good linearity observed during laboratory measurements.

Small beam excursions different for each of the cycles can be observed before beam ejection. They are related to beam orbit changes caused by RF frequency adjustments during SPS to LHC injection phase matching.

The rising and falling detector signals of the first cycle are shown in Fig. 7. For better channel comparison the DC offset voltages (mostly of the oscilloscope) were removed and the signals were normalised.

The decay of the signals is determined by the discharge of the detector parallel capacitor (1 nF) through the parallel resistor (10 MΩ), giving the 10 ms time constant. The signal rising is faster and depends on the charging speed of the parallel capacitor, which depends in addition to the capacitor value (i.e. the conversion factor of charge into voltage), also on the signal amplitude, the number of bunches present and the charging resistance, an important part of which is the dynamic resistance of the diodes.

It can be seen that the rising edge signals are very similar for both channels. This symmetry can be explored for potential orbit measurement just after beam injection, before the capacitor voltages reach their steady state values. If the symmetry is confirmed with more detailed beam measurements, then this would allow such a diode based orbit system to be used for cycling machines, like the SPS.

The quality of the presented beam measurements is determined by limited resolution of the oscilloscope acquisition (i.e. some 8 bits from the hardware and 3 bits from signal averaging). A more adequate, 24-bit acquisition system was built, but unfortunately, it could not be used with beam signals, as there have not been SPS high intensity runs since the system was ready. Such measurements will be performed as soon as adequate beam is available.

The dedicated 24-bit acquisition is based on digitisers used in the tune measurement systems [6] and modified for DC measurements. The digitisers sample at rates up to 50 kHz with signal-to-noise radio of some 110 dB for full scale signals (5 V). If the detector voltages are measured only at the 10 Hz rate, then each 5000 samples can be replaced by their average, resulting in the signal-to-noise increase by some 37 dB, resulting in the overall signal-to-noise ratio of 147 dB. This noise performance would make it possible to measure signal from the compensated diode detectors with resolution in the order of 0.2 μV, which still can be an important contribution to the overall noise performance of the whole beam orbit measurement system.

ONGOING DEVELOPMENT

The development leading to the results presented in this paper was initially targeted for the system of BPMs looking to be integrated into the next generation LHC collimator jaws. In this system signals from small button BPMs placed at the extremities of the collimator jaws will be used to position the jaws symmetrically with respect to the beam. Signals of exactly the same amplitude are expected from the opposing BPM buttons, therefore linearity of the electronics processing these signals is not that important if both signals are treated with the same multiplexed electronics chain. As a 1 μm resolution with 1 Hz reading is expected from this system, the authors, encouraged by very positive experience with sensitive diode-based tune measurement systems, started looking for a similar solution for measuring beam orbits. The compensated diode detector scheme presented here was found to have excellent resolution and very good linearity, much better than anticipated. For this reason the initial concept of diode-based orbit electronics for the LHC collimator BPMs was extended and now the development is targeted at a high resolution general purpose BPM electronics for measuring beam orbits. Its first application is still LHC collimator BPMs, but if the expected performance of the final diode electronics is confirmed, then this solution can be used for other applications requiring orbit measurement with very high resolution.

Another potential application of the compensated diode detectors is the new BPM system for the SPS. This machine requires both, trajectory and orbit measurements, therefore the idea would be to build a system containing two dedicated sub-systems, one for fast measurements with limited resolution, and the second dedicated for high resolution orbit measurements. This solution would allow

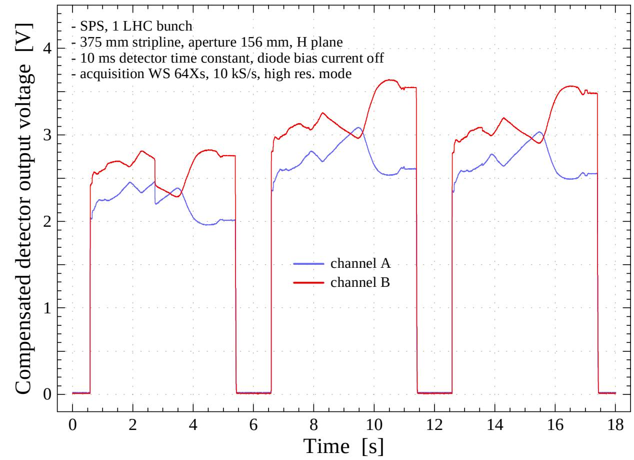

Figure 5: Compensated detector voltages for three SPS cycles with a LHC type beam.

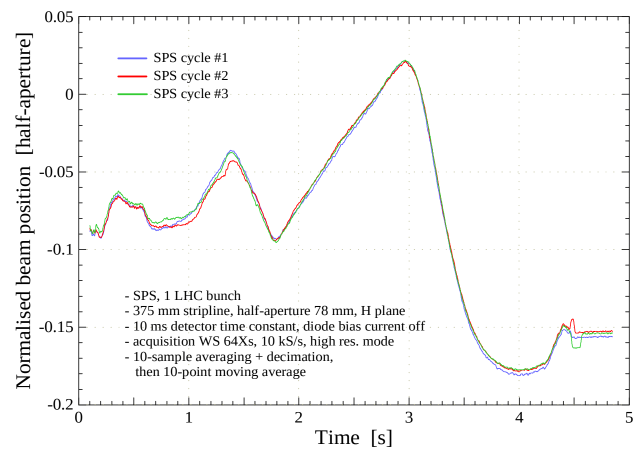

Figure 6: Beam position calculated from the detector signals of Fig. 5.

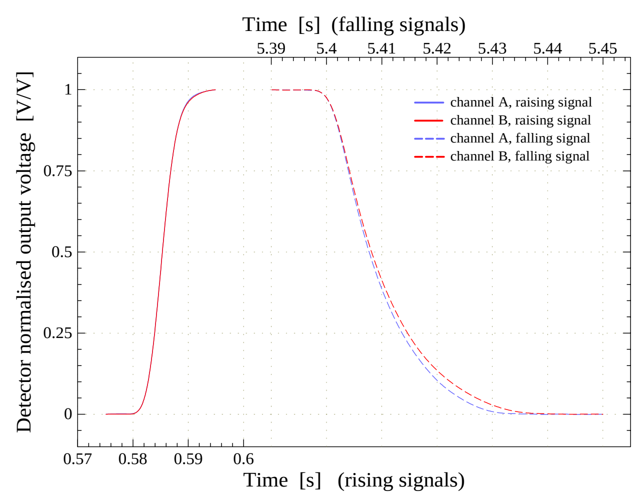

Figure 7: Normalised rising and falling signals of the first SPS cycle shown in Fig. 5.

calibration of the fast trajectory system operated in the orbit mode against the precise high resolution orbit system based on compensated diode detectors. As the diode orbit measurement circuitry is very simple and inexpensive, adding it to a more complex trajectory system would not drastically change the overall cost and complexity.

The ongoing development has to address the issue of processing low amplitude signals. Compensated diode detectors work nicely for input amplitudes larger than some hundred mVp, therefore an amplification is required if the BPM electrode signals are smaller. As the amplitude of the detector input signals should be kept between some 0.5 Vp and 5 Vp, variable gain amplifiers (VGAs) need to be used for this signal amplification. Since the gains of VGAs can be matched only to a percent level, which would be a limiting factor for the overall system accuracy, the processing channels should be multiplexed before the VGAs.

To evaluate the benefits of the multiplexing, assume that each of the peak voltages V_A and V_B from opposing BPM electrodes is measured with each of the two processing channels A and B, having gains g_a, g_b, and offsets o_a, o_b, respectively. The resulting voltages V_{m1a} and V_{m1b} measured at the same time during the first measurement and V_{m2a} and V_{m2b} from the corresponding second measurement are

$$V_{m1a} = g_a V_A + o_a\,, \quad V_{m1b} = g_b V_B + o_b \qquad (3a, 3b)$$

$$V_{m2a} = g_a V_B + o_a\,, \quad V_{m2b} = g_b V_A + o_b \qquad (3c, 3d)$$

Performing a third measurement with no signal at the channel inputs, one can evaluate the offset voltages

$$V_{m0a} = o_a\,, \quad V_{m0b} = o_b \qquad (4a, 4b)$$

If the beam position is calculated similarly to (1) but using signals from all three measurements according to

$$p_{AB} = c_{AB} \frac{\left(V_{m1a} - V_{m1b}\right) + \left(V_{m2b} - V_{m2a}\right)}{V_{m1a} + V_{m1b} + V_{m2a} + V_{m2b} - 2V_{m0a} - 2V_{m0b}} \qquad (5)$$

then substituting (3) and (4) into (5) results in

$$p_{AB} = c_{AB} \frac{\left(g_a + g_b\right)\left(V_A - V_b\right)}{\left(g_a + g_b\right)\left(V_A + V_b\right)} = c_{AB} \frac{V_A - V_b}{V_A + V_b} \qquad (6)$$

making the beam position independent of the channel gains and offsets, assuming only that they do not vary between the two measurements.

The difficulty in using (5) for compensated diode detectors is that the offset voltages of the processing channels cannot be evaluated from a simple measurement without input signals because the detector conversion characteristic is highly nonlinear for small signals. As the VGA outputs will be AC-coupled to the inputs of the compensated diode detectors, the detectors will determine the overall channel offsets. The offsets can be evaluated by extrapolating to zero the conversion characteristic measured at least with two known input amplitudes (see fit coefficients in Fig. 3). Whether this procedure has to be done only once in the laboratory or needs to be repeated as an online calibration depends on the time scale of offset variations and required measurement accuracy. This is being addressed in the ongoing development.

The VGAs currently on the market as integrated circuits and which would be suitable for the project have bandwidths in the order of 100 MHz. To work with nanosecond pulses such VGAs require low-pass filtering on the input, which reduces the signal peak voltages. This in turn requires more gain from the VGAs. The low-pass filters will be in the processing chain after the multiplexer, so the limited match of the filter attenuation will be removed by the multiplexing.

CONCLUSIONS

Laboratory measurements show that the compensated diode peak detectors work very well with signals of amplitudes larger than some hundred mV, achieving a channel match of about 1 mV and measurement resolution better than 1 µV for a 10 ms detector time constant and 100 ms measurement time. The measurement noise introduced by the detectors and a 6-digit laboratory voltmeter were of a similar order.

The initial results from prototype testing in the CERN-SPS are encouraging. Further studies with dedicated beam time will now be required to fully characterise this high resolution technique under varying beam configurations.

If these beam measurements confirm those of the laboratory, then a general purpose beam orbit measurement electronics based on the diode compensated detectors will be developed. Resolutions in the order of 1 ppm of BPM aperture are expected with measurement rates in the Hz range. The largest development challenge is addressing the linearity degradation for small input signals.

The first application of the diode orbit measurement system will be for the BPMs integrated into the next generation LHC collimator jaws.

With the potential that this technique could be used to measure beam orbits at Hz rates using readings from a high resolution DC voltmeter, the authors decided to publish these first results of the diode orbit measurement development at an early stage. The hope being to encourage the beam instrumentation community to study this technique in parallel to the CERN efforts.

The compensated diode detectors may find application in systems with fast signals, whose slow varying amplitudes should be measured with very high resolution.

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